Monitoring Air-Sea Exchange Processes Using The High Frequency Ambient Sound Field

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LONG-TERM GOAL

The ambient sound field contains information about the processes generating the sound and the intervening media modifying the sound. This research seeks to demonstrate measurement of useful ocean surface processes using passive measurements of the high frequency underwater ambient sound field. This will allow passive monitoring of environmental conditions from simple and robust sensors, namely hydrophones. In turn, given environmental weather conditions, predictive Naval ocean ambient noise models will be improved. This technique introduces no acoustic disturbance to the environment, and is hence covert and poses no potential harm to marine mammals or other forms of life in the ocean.

The frequency range of interest is roughly 200 Hz to 50 kHz. In this frequency range, the dominant sources of sound are breaking wind waves and precipitation. The sound generated by these phenomena can be subsequently modified by ambient bubbles. Breaking waves, precipitation and bubbles are an important part of the exchange of momentum, heat, water and gas between the ocean and the atmosphere. Coupled air-sea models are currently the weakest of the numerical models needed to analyze and forecast environmental (weather) conditions. Modelers have identified the need for data, especially of wind and rain, to develop and verify these models. Acoustical inversion of the sound field should be able to provide these data, even in remote and difficult regions where more conventional measurements are unavailable.

SCIENTIFIC OBJECTIVES

Inversion of the underwater ambient sound field consists of two general components: identifying the source of the sound, and then quantifying it. Acoustic classification of weather (Nystuen and Selsor, 1997) has identified four ocean surface features producing distinctive features in the sound spectrum from 1-50 kHz. These are wind, drizzle, heavy rain and ambient bubbles present (Fig. 1). The robustness of the classification needs further development. In particular, the situation of rain in the presence of high wind apparently generates a dense ambient bubble layer at the ocean surface. How does the modification of the sound spectrum by these bubbles affect classification? The ambient sound field is also known to have regional and temporal variations. How does this variability affect classification?

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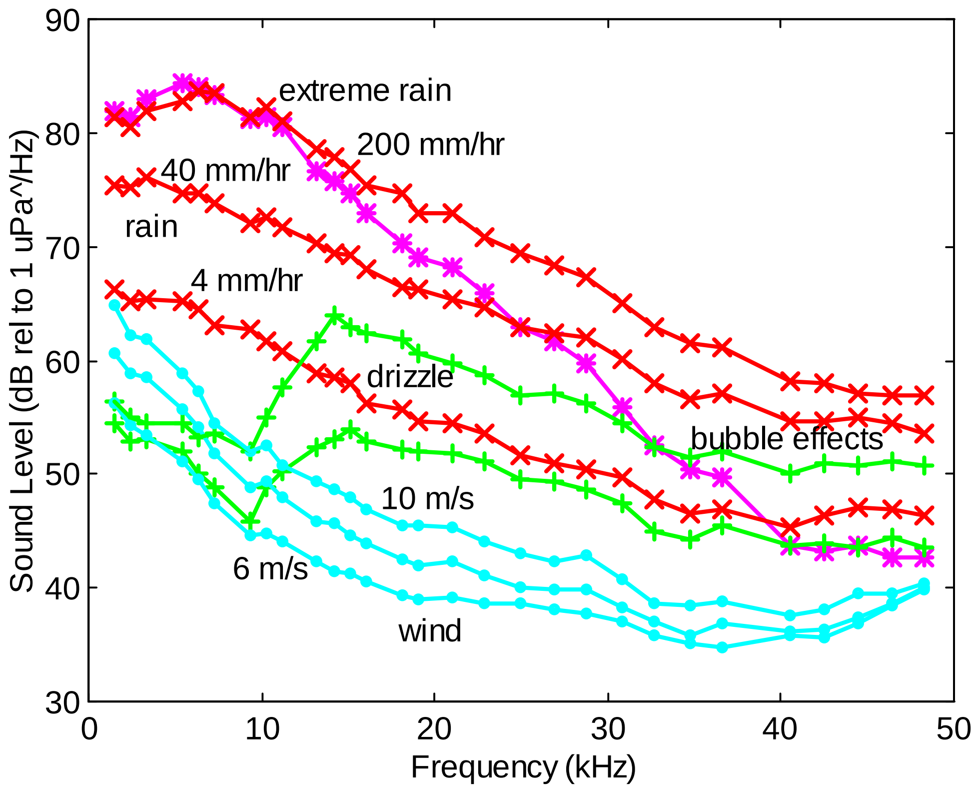

Figure 1. Examples of oceanic sound spectra for wind, rain, drizzle and extreme rain (200 mm/hr) from the South China Sea. One of the spectra for extreme rain shows depressed high frequency (over 20 kHz) sound levels due to absorption by a sub-surface ambient bubble layer. It was recorded five minutes after the other extreme rain spectrum. This indicates that extreme rain is injecting bubbles into the ocean surface.

Once classification is obtained, there are several algorithms available to quantify wind speed (Vagle et al., 1990) and precipitation (Nystuen et al. 1993; 1996; 1999). Again, the robustness of these algorithms in different environmental conditions needs to be validated, and limitations to the inversions identified and documented. In particular, the interaction of wind and rain together needs further examination. In low wind conditions, the inversion of the rain generated sound field yields estimates of the full drop size distribution in the rain. This is a very good measurement of rainfall, allowing identification of rainfall type as well as rainfall rate (Nystuen, 1997b; 1999). However, wind limits the detection of small raindrops, representing a limitation to the technique including the overall detection of drizzle. The influence of wind on the inversion for rainfall needs to be further documented.

One of the more exciting new directions of this research is the quantitative estimation of ambient bubble populations using the passive ambient sound field. Conditions generating detectable ambient bubbles include high winds alone (Farmer and Lemon, 1984), very heavy rainfall (Fig. 1) and, especially, rain in the presence of high wind. These passive acoustic void fraction estimates need to be documented and compared to available ancillary measurements. The presence of these bubbles suggest that periods of enhanced gas exchange can be detected using passive acoustics.

TECHNICAL APPROACH

Multiple ocean ambient sound data sets have now been obtained and several more are anticipated. These data sets include: OASIS (North Sea at 2000 m, Zedel et al. 1999), ASREX (North Atlantic, mid-winter), SCSMEX (South China Sea monsoon season, Lau, 1998), ANS Drifters (various locations worldwide), MARS (Miami sheltered pond, rainfall). New data sets are anticipated, including from the tropical Pacific Ocean warm pool region, ITZC and the stratus deck region near Peru, and other opportunities. These data sets include various ancillary information which can be used to verify the performance of the different acoustic inversion algorithms. By intercomparing the measurements from these different regions and environmental conditions, it is expected that regional and seasonal limitations to the technique will be identified and documented. A particular focus will be placed on rainfall detection, classification and quantification as the newer data sets, e.g., SCSMEX, include better and better ancillary rainfall information. The application of acoustic algorithms developed using the MARS data set to exposed ocean conditions is of particular interest.

WORK COMPLETED

The MARS rainfall data set has been analyzed to document the potential and the limitations of the acoustical inversion to quantitatively measure raindrop size distribution within rain (Nystuen, 1997b; 1999). The drifter data set has been analyzed to validate acoustic wind speed measurements and rainfall detection by comparison to passive microwave satellite data (Nystuen, 1997c). The ASREX data set has been analyzed to produce a climatic-type rainfall record for the duration of the experiment and to provide rainfall rate data for process studies on the influence of rain on other air-sea exchange processes. The ASREX data also demonstrate the potential of using the ambient sound field to quantitatively estimate ambient bubble populations in the near-surface layer of the ocean. Two acoustic rain gauges (ARGs) were designed, built, tested and deployed on deep ocean surface moorings. Data from their deployment in the South China Sea Monsoon Experiment (SCSMEX) demonstrate acoustic detection of rainfall and the potential to classify rainfall type (Nystuen et al., 1999). Vandalism is a serious problem for surface instrumentation at sea. The ARGs on the SCSMEX mooring, covert and undetected 20 m underwater, were the only instrumentation to survive an act of piracy, and continued to provide data for the experiment after the attack. A new generation Acoustic Rain Gauge (ARG) has been designed and built. The new ARGs are being deployed for the first time in December 1999 and will be returning their first data from oceanic moorings in 2000.

RESULTS

Because different raindrop sizes produce sound underwater by different physical mechanisms, the underwater sound can be decomposed into components associated with each drop size category. These drop size categories have been carefully documented and show that the acoustic inversion can be used to identify changing drop size distributions within rain, allowing classification of rainfall type. Rainfall rate, the most often desired end product, is determined by summing the contribution from each drop size category. When compared to five other types of automatic rain sensors (Nystuen, 1999), the acoustical measurement is correlated to the other gauges with a correlation coefficient of roughly 0.9. The single most important factor affecting the acoustic measurement is the presence or absence of very large raindrops (over 3.5 mm diameter) within the rain. These drops are extraordinarily loud underwater and dominate the sound field when present. If these very large raindrops are not properly detected, then the smaller drop size populations are poorly estimated. In particular, the medium raindrop size category (1.2-2.0 mm diameter) is relatively quiet underwater, and consequently, relatively hard to measure acoustically. In contrast, the small raindrops (0.8-1.2 mm diameter) are relative loud underwater and easily detected acoustically.

The first step in the analysis of oceanic ambient sound data is to identify the present surface weather conditions (wind, drizzle, heavy rain, ambient bubbles present) (Nystuen and Selsor, 1997). Oceanic ambient sound measurements from 15 autonomous surface drifters were compared to passive microwave satellite (SSM/I) measurements of surface wind speed, atmospheric liquid water (cloud and rain drops) and rainfall (Nystuen, 1997c). The correlation between acoustic and satellite wind speed estimates was 0.91 (254 data points). The acoustic wind speed measurement showed no regional or environmental variability, but was biased low compared to the satellite measurement by 0.8 m/s. Of 21 acoustically detected precipitation events (both drizzle and heavier rain), the satellite measurements confirmed 19 (90% detection rate). Given unproven algorithms and the mismatch of temporal and spatial sampling by the drifter and the satellite sensors, quantitative comparisons are difficult to evaluate. The wind speed threshold for acoustic detection of light rain and drizzle is 8-10 m/s (Nystuen, 1997c; OASIS data analysis).

Another oceanic data set, from ASREX, was analyzed to produce a 90 day record of the rainfall. An estimated 477 mm of rain fell, including 5 storms with more than 20 mm of rain accumulation. The temporal detection of rain (drizzle 3.0 % of the time; heavier rain 2.4% of the time) are the type of statistics needed by climatologists (Petty, 1995). Not only do these data demonstrate the potential for climatological rainfall measurements, they also allow the first opportunity to examine the influence of rainfall on other air-sea processes, for example, near surface salinity, surface waves, gas exchange, etc. In particular, 1-m salinity measurements showed very large “fresh water” fluxes during extended periods of light rain/drizzle, but had a very different character during heavier rain when the winds were higher. The ASREX data set also shows evidence of bubble injection into the mixed layer by rain. Whenever rain occurs during high wind speed (over 10 m/s) conditions, the spectral slope above 10 kHz steepens, an indication of bubbles being mixed downward deeply enough to change the ambient sound field. By examining the change in spectral slope, quantitative estimates of near-surface void fraction compare well to ancillary void fraction measurements.

A third oceanic data set, SCSMEX, has allowed direct comparison of a mooring-mounted rain gauge with Acoustic Rain Gauges (ARG) (Nystuen et al., 1999). The instruments show agreement for the detection of rainfall and measurement of rainfall rate. Furthermore, comparison with ancillary weather radar data demonstrate the ability of the ARGs to classify rainfall type. This classification of rainfall type is important to meteorologists as different types of rainfall have different heating profiles in the atmosphere, and rainfall rate measurements from weather radars are improved if rainfall type is part of the measurement algorithm.

IMPACT/APPLICATIONS

Analysis of the ambient sound field to provide important air-sea exchange measurements is a technology that should lead to important advances in our understanding of the physics of the air-sea interface. The measurement is simple, robust and covert. It can be made from small, autonomous drifters, or larger surface moorings. The measurements of wind, precipitation and bubbles are difficult to make by more conventional means, and are critical components of vital air-sea fluxes of heat, water, momentum and gas that drive the interaction of the atmosphere and the ocean. Coupled air-sea models are currently the weakest of the numerical models needed to analyze and forecast environmental (weather) conditions on small, regional and global scales. These modelers have identified the need for data, especially of wind and rain, to develop and verify these models.

TRANSITIONS

The Tactical Oceanography Warfare Support (TOWS) program at NRL has sponsored the development of air-deployable autonomous drifters (Selsor, 1993). Navoceano and NOAA are now deploying these sensors on a regular, but limited, basis (about 20 per year). The NOAA National Data Buoy Center is interested in "no-moving-parts" sensors for wind and precipitation. They are actively exploring the potential application of this technology for their platforms. As part of the NOAA Pan-American Climate Studies (PACS) program, ARGs are to be mounted on some of the NOAA Tropical Atmosphere Ocean (TAO) array moorings. It is proposed that the acoustic sensors become a regular component of the NOAA TAO tropical ocean mooring array, and be regularly deployed as part of other large oceanic field experiments. ARGs have also been deployed as part of the NASA Tropical Rain Measuring Mission (TRMM) surface validation field programs (SCSMEX and KWAJEX).

RELATED PROJECTS

"Acoustical Rainfall Analysis", sponsored by the Ocean Sciences Division, Physical Oceanography, of the National Science Foundation, broadly overlaps this project. The goal of this NSF project is to develop the acoustical inversion technology to provide a means of making oceanographic rainfall measurements. This project has funded the development of the new generation ARG and their anticipated deployment in the western tropical Pacific Ocean.

"Long-term Measurements of Air-Sea Processes: Rainfall, stratiform drizzle, ambient bubbles, and wind speed" is sponsored by the NOAA Pan-American Climate Studies (PACS) program. Its goal is to apply the acoustical weather analysis technology to obtain climatic rainfall data. This project uses the new ARG instruments, three of which have recently been deployed in the eastern tropical Pacific Ocean on the Tropical Ocean Atmosphere (TAO) deep ocean mooring array maintained by NOAA.

"Validation of Acoustical Rainfall Measurements" is sponsored by the NASA TRMM Program Office. This project focuses on the evaluation of different types of acoustical rainfall measurement algorithms. An emphasis on acoustical classification of rainfall type will use the comparison of weather radar data with the acoustical measurements.

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